X-611-69-348
PREPRINT

NASA TM X- 63654

CO-ROTATING MODULATIONS OF COSMIC RAY INTENSITY DETECTED BY SPACECRAFT SEPARATED IN SOLAR AZIMUTH

V. K. BALASUBRAHMANYAN
E. C. ROELOF
R. P. BUKATA
R. A. R. PALMEIRA

AUGUST 1969

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

CO-ROTATING MODULATIONS OF COSMIC RAY INTENSITY DETECTED BY SPACECRAFTS SEPARATED IN SOLAR AZIMUTH*

by

V. K. Balasubrahmanyan & E. C. Roelof**
NASA/Goddard Space Flight Center
Greenbelt, Maryland

R. P. Bukata & R. A. R. Palmeira
Southwest Center for Advaced Studies
Dallas, Texas

ABSTRACT:

The daily cosmic ray intensity from the IMP-C (Explorer XVIII) geiger-counter monitor ($E_p \gtrsim 50$ MeV) and Pioneer VI scintillation telescope ($E_p \gtrsim 7.5$ MeV) have been statistically analyzed by the use of correlation functions. When the two spacecrafts are close to each other, the cross-correlation function agreed closely with the auto-correlation function of either detector, showing that both detectors were responding comparably and reliably to cosmic ray fluxes. When Pioneer VI and IMP-C were separated by $\sim 50^{\circ}$ (October-December 1966), the variations in the detector rates appear to be mainly due to galactic cosmic rays. Solar flare contributions $\gtrsim 7.5$ MeV have been eliminated from the Pioneer VI data by regression analysis using low energy rates (7.5 MeV $\lesssim E_p \lesssim$ 44 MeV). Comparison of IMP-C and neutron monitor rates shows no detectable variations in solar proton outflow of $E_p \gtrsim 50$ MeV. The cross-correlation function between the detectors during this

*Presented to the 11th International Conference on Cosmic Rays, Budapest, Hungary.

**NAS/NASA Resident Postdoctoral Research Associate. Present address, Department of Physics, University of New Hampshire, Durham, N.H.

quiet period reaches a significant peak (0.67 ± 0.05) with a lag of ~ 3 days between data from IMP-C and Pioneer VI. Also, the cross-correlation function (displaced by -3 days) is qualitatively similar in form to the auto-correlation function from IMP-C. It is proposed that there are numerous long-lived regions of modulated cosmic ray flux following the general spiral configuration of the inter-planetary magnetic field as the field structure co-rotates with the sun. This interpretation is consistent with the observations of recurrent Forbush decreases in early 1966 reported by McCracken, Rao, and Bukata (1966).

Introduction

It is well known that the interplanetary magnetic field controls the propagation of cosmic rays in the solar system. Low energy cosmic rays of solar or galactic origin remain linked to the magnetic tube of force along which they are propagating. Since the magnetic field is "frozen" in and convected by the solar wind, co-rotation of cosmic ray particles with the sun could result. For solar flare particles O'Gallagher and Simpson (1967), McCracken et al. (1967), and Lin et al. (1968) have presented evidence for co-rotation and studied the azimuthal dependence of their propagation. The studies of Bryant et al. (1965), and McCracken et al. (1966) on recurrent modulation phenomena have resulted in much information on co-rotating shock fronts where low energy particles may be continuously accelerated (Rao et al., 1967) and galactic particles are modulated in a manner similar to Forbush decreases. These regions have a long life time and have been followed through several solar rotations.

In the case of galactic cosmic rays, the diurnal anistropy and the 27 day recurrent Forbush decreases are prime examples of the co-rotation effect. Bukata et al. (1968), using their Pioneer VI and VII detectors, separated in solar azimuth by ~53°, have studied Forbush decreases associated with solar flares (blast waves) as well as recurrent co-rotating shock

fronts. All the above phenomena deal with reasonably disturbed conditions in the interplanetary magnetic field. In this paper the results from the cosmic ray monitors on Explorer XVIII and Pioneer VI are compared during a quiet time. The co-rotation phenomena associated with quiet time conditions are studied to obtain information regarding the spatial and temporal structure of the interplanetary field and its interaction with galactic cosmic rays.

Experimental Details

The IMP-C GM counter monitors the omnidirectional intensity of protons with energies above ~50 MeV. The threshold energy for detected electrons is ~4 MeV. The counting rate of the monitor is ~100/sec resulting in a daily statistical accuracy of ~.1%. The satellite was launched on May 9, 1965 into a highly eccentric geocentric orbit of apogee 41.5 R_E with a period of 5.8 days covering the entire period of interest in this paper, the monitor behaved very reliably. An inflight comparison with a similar detector aboard OGO-1 has shown that there were no detectable long term drifts in the behavior of the counter. A detailed description of the GM counter monitor may be found in Balasubrahmanyan et al. (1965).

The Pioneer VI data were obtained from the scintillation counter telescope experiment to study the azimuthal anisotropy of solar and galactic cosmic rays. The data considered in

this paper consist of the cosmic ray intensity for particles with energy > 7.5 MeV. The detector characteristics and other essential experimental information are described in detail by Bartley et al. (1967) and McCracken et al. (1967). Solar particle contribution to the data has been eliminated by a method involving a regression analysis of the integral intensity channel (> 7.5 MeV) and the channel for particles with energy between 7.5 MeV and 45 MeV. This procedure is described in the work of McCracken et al. (1966) and Bukata et al. (1968). Pioneer VI was launched into solar orbit on December 16, 1965. During the early part of 1966 the satellite-sun-earth angle remained small, increasing gradually to $\sim 53^{\circ}$ by the end of the year. Its radial distance from the sun varied between 1.22×10^{8}km to 1.47×10^{8}km. Fig. (1) shows the **angular and radial** coordinates of Pioneer VI during 1966. The trajectory of the satellite lies in the ecliptic plane.

Results

The Pioneer VI solar azimuth during the first eighty-five days of 1966 was less than 5°. There was extensive data coverage for both the IMP-C and Pioneer VI spacecrafts during this period resulting in very little missing data.

Fig. (2) shows the regression plot of the daily average counting rates from IMP-C and Pioneer VI for the first 85 days of 1966. The correlation coefficient is .96 and the

excellent agreement between the data from the two detectors shows that both instruments are responding reliably and comparably to cosmic ray fluxes. Also plotted in the figure are monthly averages from the two satellites for the entire period. These monthly averages line up very well along the linear regression plot of the daily rates, showing that there has been no appreciable systematic long term drift of the detectors. This observation provides a measure of confidence for the analysis performed for the later period (after day 240) when data coverage in Pioneer VI data becomes spotty.

From day 240 onwards the azimuthal angle Φ remains approximately 52°. September was disturbed by a number of solar events. The period after day 276 up to the end of the year was relatively quiet and was considered in this study.

The daily average counting rates of the Deep River neutron monitor, IMP-C, and Pioneer VI (when available and corrected for solar out flow) for this period are shown in Fig. (3). There are three noticable decreases commencing on October 23, November 16, and December 12. The latter two are separated by 27 days (suggesting a recurrent event) but the first two are 24 days apart while their minima are only 21 days apart. The Forbush decrease of December 12 has been studied in detail (Bukata, et al., 1968) and comparison of data from Pioneer VI and Pioneer VII (the latter then near the earth) established that it was not a co-rotating structure.

It should be emphasized that the three detectors used to obtain the data plotted in Fig. (3) have thresholds of ~ 10 MeV, 100 MeV and 1000 MeV. Thus we may establish that low energy galactic cosmic rays over two decades of energy display similar co-rotating phenomena. Although such features are apparent in Fig. (3) we have applied the more rigorous technique of cross-correlation to the analysis of the data.

The cross-correlation function of the Deep River neutron monitor daily averages N(t) and the IMP-C averages I(t) is presented in Fig. (4) along with the even auto-correlation functions of N(t) (plotted for positive lag), and I(t) (plotted for negative lag). The similar behavior of the two detectors is established not only by the high cross-correlation at zero-day lag (0.9) but by the near-equality of all three functions for lags up to 30 days. The average period of the damped quasi-sinusoidal oscillations that dominate the functions is 11 - 12 days but such a period is not readily apparent from inspection of Fig. (3). It is more likely the "signature" of the three large decreases. The half-width of the central peak (~ 3 days) is also the approximate half-width (including precursors) of the three large decreases.

The cross-correlation function of I(t) and N(t) with P(t) (Pioneer VI daily averages) are shown in Fig. (5). They are seen to exhibit strong peaks (~ 0.67 ± 0.05) at a lag of +3 days, and the general similarity to the cross-

correlation functions of Fig. (4) is clear. The strong peak of 0.7 at a delay of + 3 days in the cross-correlation function $<I(t)\ P\ (t + \tau)>$ is still present <u>even after a removal of the contribution of the obvious co-rotating decrease of October 24 from the two species of data.</u> This indicates that the high cross-correlation is not dictated solely by the presence of a single well-defined co-rotating event. A shift of the main peak to $\tau = 4$ days is expected for co-rotation, so some additional azimuthal evolution of features is implied by the observed 3-day shift. There are additional structures in Fig. (5) that are statistically significant, particularly the increase at $\tau = -23$ days. This increase appears to be related to the increase at a corresponding lag of -27 days in $< I(t)\ I\ (t + \tau) >$ depicted in Fig. (4). This may be a 27 day recurrence tendency that is more pronounced at lower energies, such as could be produced by outflow that is not completely removed from the Pioneer data by the regression technique and is also present at the higher energies detected by IMP-C. However, the presence of the feature also at $\tau = -24$ days in $< N(t)\ P\ (t + \tau) >$ suggests that the particles responsible for this 27 day recurrence tendency are more likely to be galactic cosmic rays. This discussion illustrates the ambiguity in cross-correlation analysis between recurrent solar outflow and galactic decreases, both of which give a positive cross-correlation.

Conclusions

The co-rotation of quiet-time modulations of cosmic rays from 10 MeV to 1 BeV has been established by statistical techniques. The strong correlation of the data from three observation stations implies all three are responding to galactic cosmic rays during the period under consideration here. Therefore, short-term modulation of galactic cosmic rays during undisturbed periods may, in general, be predominantly due to co-rotating magnetic structures. Since the mechanism of such modulations is not firmly established, care should be exercised in applying current theories to short-term variations of low energy galactic cosmic rays.

This study illustrates the need to consider the role of the co-rotation effect in studies of gradient of cosmic rays in the solar system with detectors separated appreciably in the solar azimuth. Krimigis & Venkatesan (1969) discuss the inappropriateness of the inclusion of Forbush decreases in studies of the cosmic ray intensity gradient determined with detectors in orbit around the earth and carried in Mariner IV. It is clear from the results presented here that if a modulation phenomenon is observed by a detector at some point in the inner solar system, another detector separated Θ degrees in solar azimuth may also observe this modulation phenomenon. The time delay between successive observations of such a phenomenon would be given by $\sim \Theta / 13.3$ days.

References

Balasubrahmanyan, V. K., G. H. Ludwig, F. B. McDonald, and R. A. R. Palmeira, "Results From the IMP-I GM Counter Telescope Experiment", J. Geophys. Res., 70, 2005-2019, 1965.

Bartley, W. C., K. G. McCracken, and U. R. Rao, "The Pioneer 6 Detector To Measure the Degree of Anistropy of the Cosmic Radiation in the Energy Range 7.5-90 MeV/nucleon", Rev. Sci. Instr., 38, 266-272, 1967.

Bryant, D. A., T. L. Cline, U. D. Desai, and F. B. McDonald, "Continual Acceleration of Solar Protons in the MeV Range", Phys. Rev. Letters, 14, 481, 1965.

Bukata, R. P., K. G. McCracken, and U. R. Rao, "A Comparison of the Characteristics of Corotating and Flare-initiated Forbush Decreases", Can. J. Phys., 46 S994-S998, 1968.

Krimigis, S. M. and D. Venkatesan,"The Radial Gradient of Interplanetary Radiation Measured by Mariners 4 and 5", J. Geophys. Res. 74, 4129-4146, 1969.

Lin, R. P., S. W. Kahler, and E. C. Roelof, "Solar Flare Injection and Propagation of Low-Energy Protons and Electrons in the Event of 2-9 July 1966", Solar Physics 1, 338-360, 1968

McCracken, K. G., U. R. Rao, and R. P. Bukata, "Recurrent Forbush Decreases Associated with M-Region Magnetic Storms", Phys. Rev. Letters, 17, 928-932, 1966.

McCracken, K. G., U. R. Rao, and R. P. Bukata, "Cosmic-Ray Propagation Processes, 1. A Study of the Cosmic-Ray Flare Effect", J. Geophys. Res., 72, 4293-4324, 1967.

O'Gallagher, J. J. and J. A. Simpson, "The Heliocentric Intensity Gradients of Cosmic-Ray Protons and Helium During Minimum Solar Modulation", Astrophys. J., 147, 819, 1967.

Rao, U. R., K. G. McCracken, and R. P. Bukata, "Cosmic-Ray Propagation Processes, 2. The Energetic Storm Particle Event", J. Geophys. Res., 72, 4325-4342, 1967.

Figure Captions

Fig. 1 Solar distance (R) of Pioneer VI and angle (ϕ) westward from earth.

Fig. 2 Regression plot of the daily average counting rates from IMP-C and Pioneer VI for days 1 - 85, 1966. Also plotted are monthly averages for the first 11 months of the Pioneer VI mission.

Fig. 3 Daily average counting rates for the three detectors compared in this study: Pioneer VI scintillation telescope, IMP-C Geiger monitor, and Deep River neutron monitor.

Fig. 4 Auto-and cross-correlation functions for IMP-C Geiger monitor (I) and Deep River neutron monitor (M). The autocorrelation functions, being even, are plotted only for positive lags (N, open circles), and negative lags (I, open squares).

Fig. 5 Cross-correlation functions for IMP-C Geiger monitor (I, closed circles) and Deep River neutron monitor (N, open circles) with the Pioneer VI scintillation telescope (P).

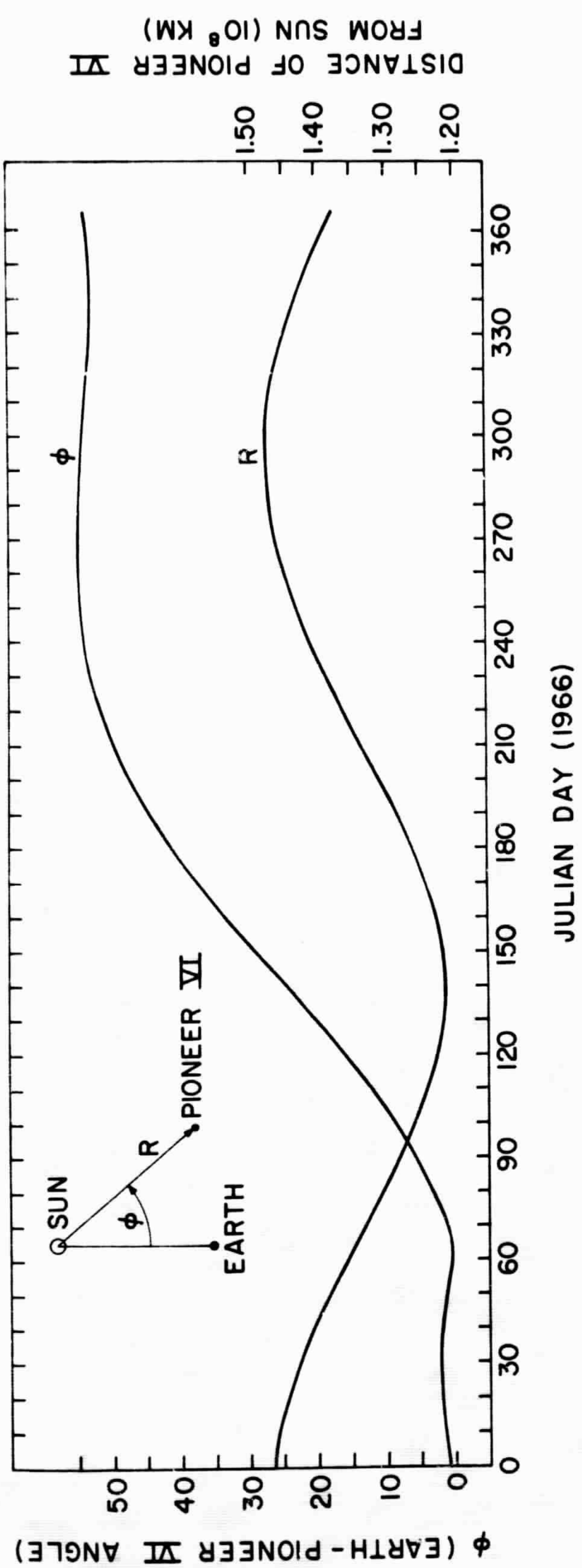

DISTANCE OF PIONEER VI FROM SUN (10^8 KM)
1.50
1.40
1.30
1.20
ϕ (EARTH-PIONEER VI ANGLE)
50
40
30
20
10
0
JULIAN DAY (1966)
0
30
60
90
120
150
180
210
240
270
300
330
360
ϕ
R
SUN
R
ϕ
PIONEER VI
EARTH

Fig. 1

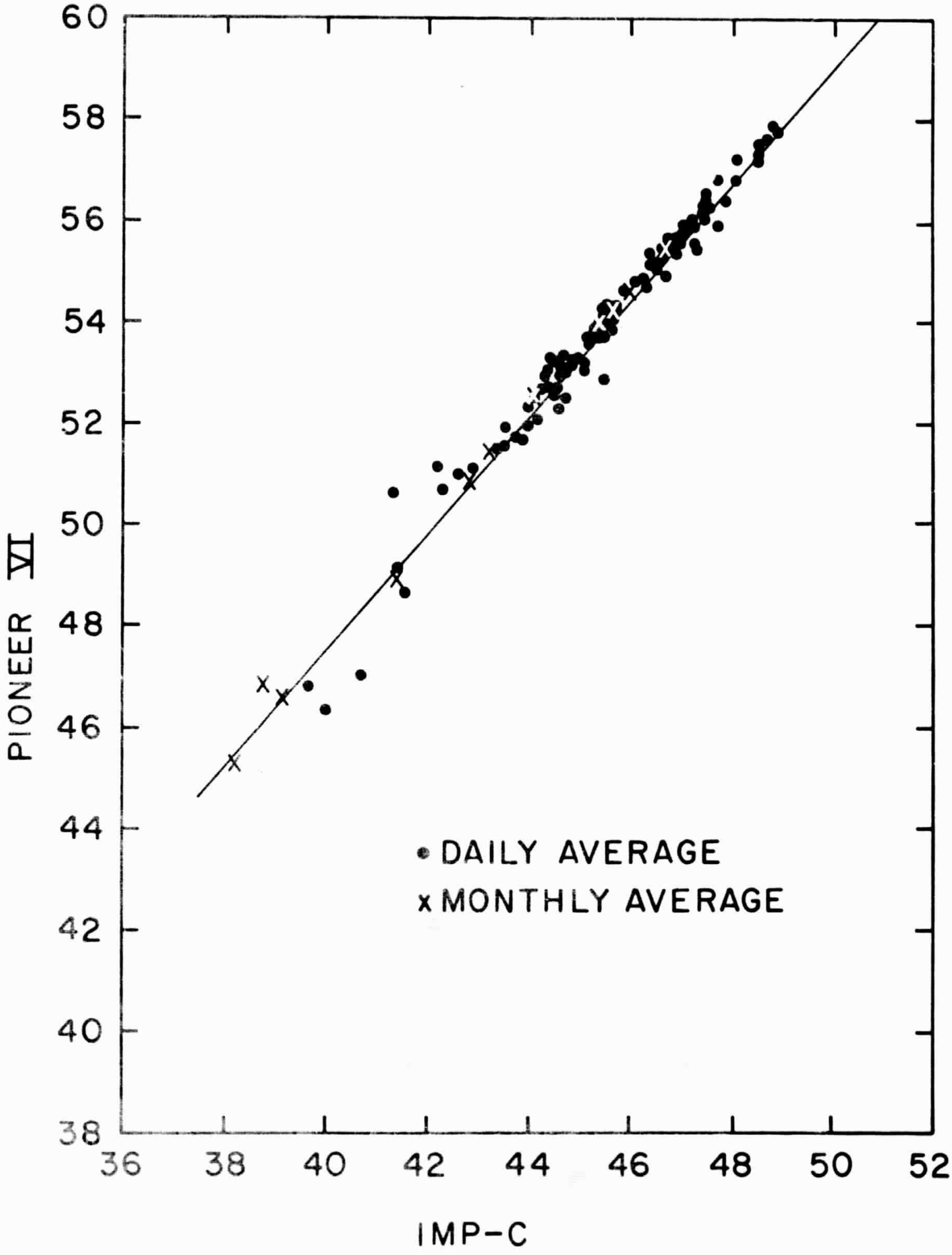
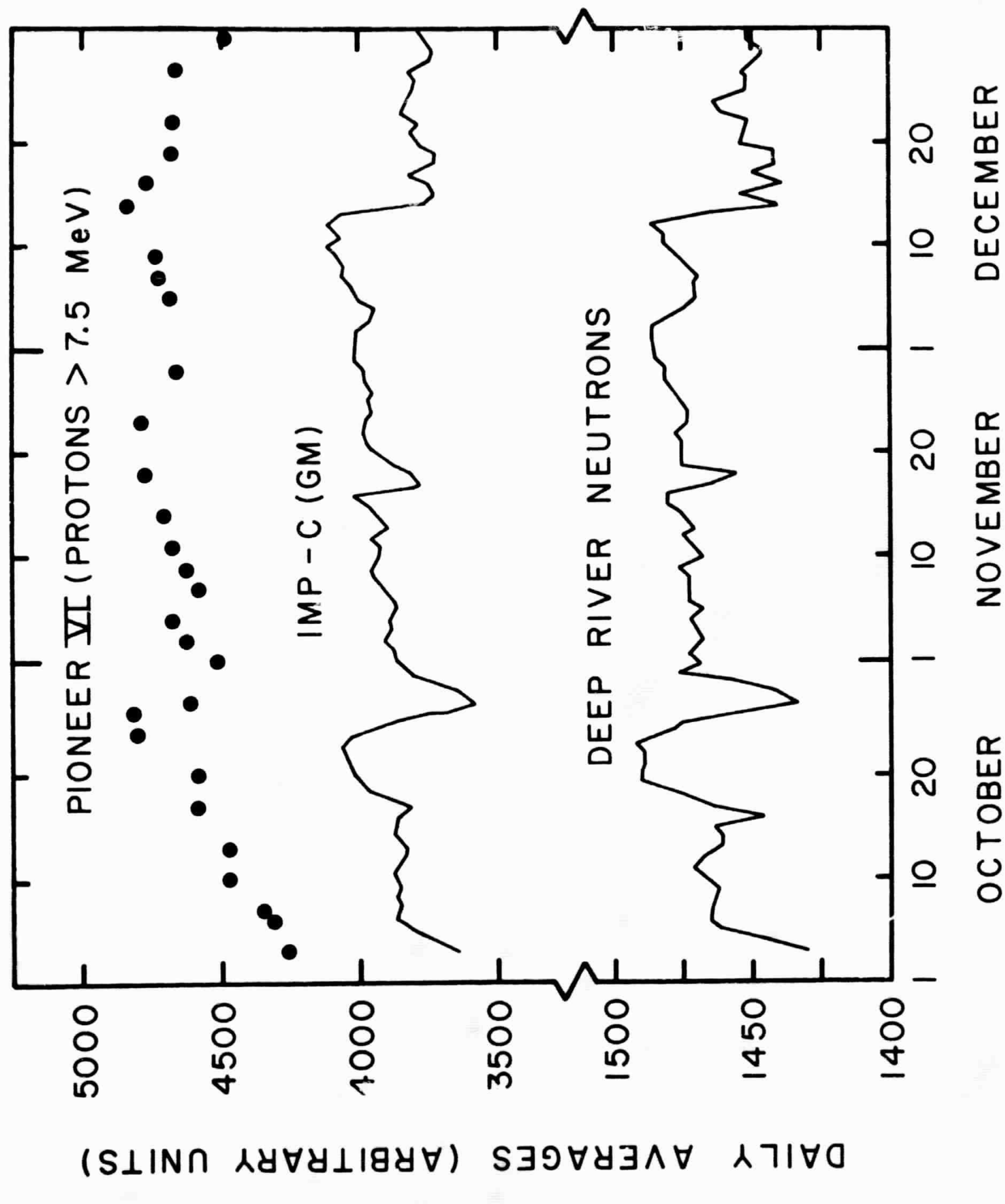

60
58
56
54
52
50
48
46
44
42
40
38
36
38
40
42
44
46
48
50
52
PIONEER VI
IMP-C
• DAILY AVERAGE
x MONTHLY AVERAGE

Fig. 2



PIONEER VI (PROTONS > 7.5 MeV)
IMP - C (GM)
DEEP RIVER NEUTRONS
5000
4500
4000
3500
1500
1450
1400
DAILY AVERAGES (ARBITRARY UNITS)
1
10
20
OCTOBER
NOVEMBER
DECEMBER
1966

Fig. 3

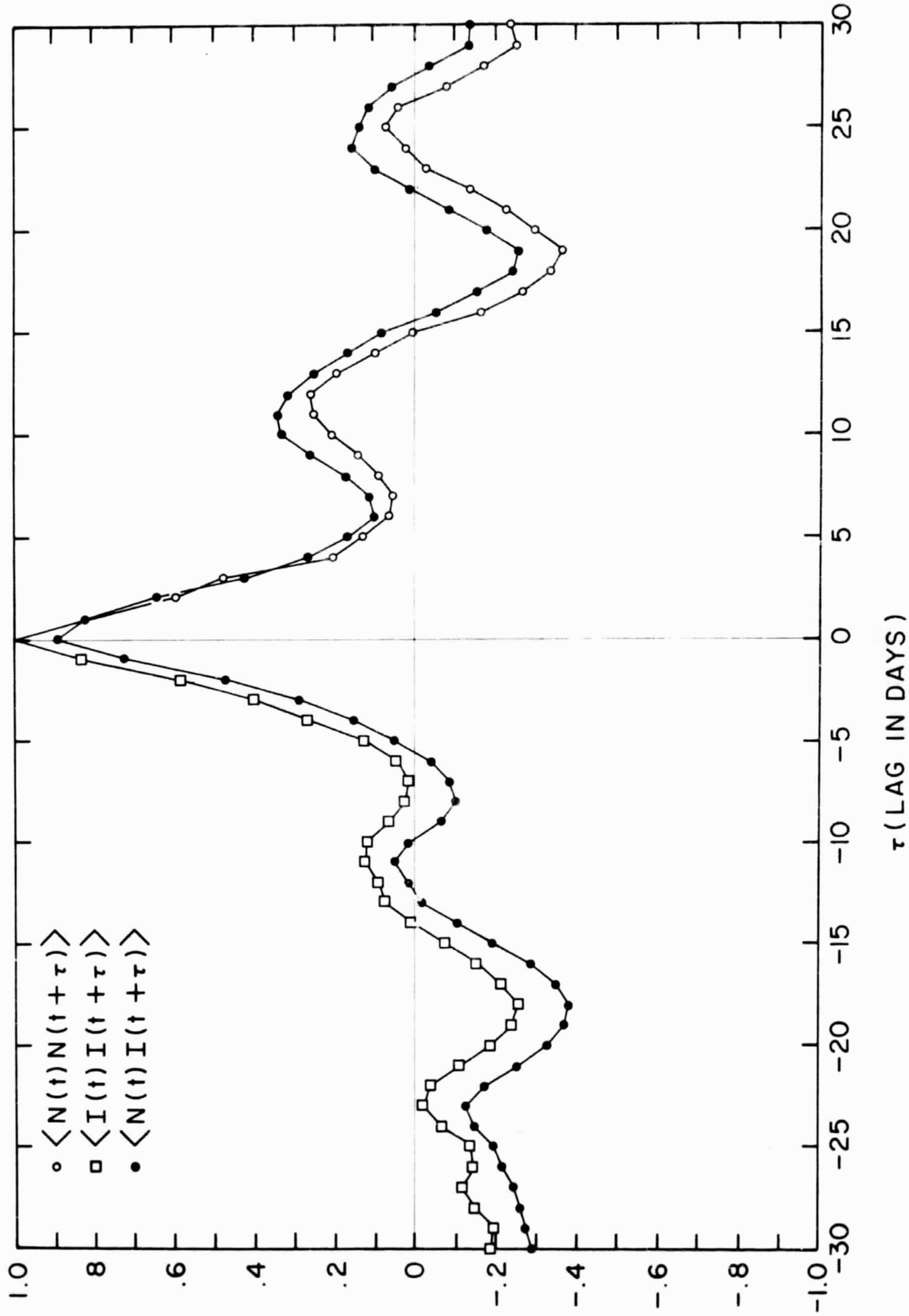
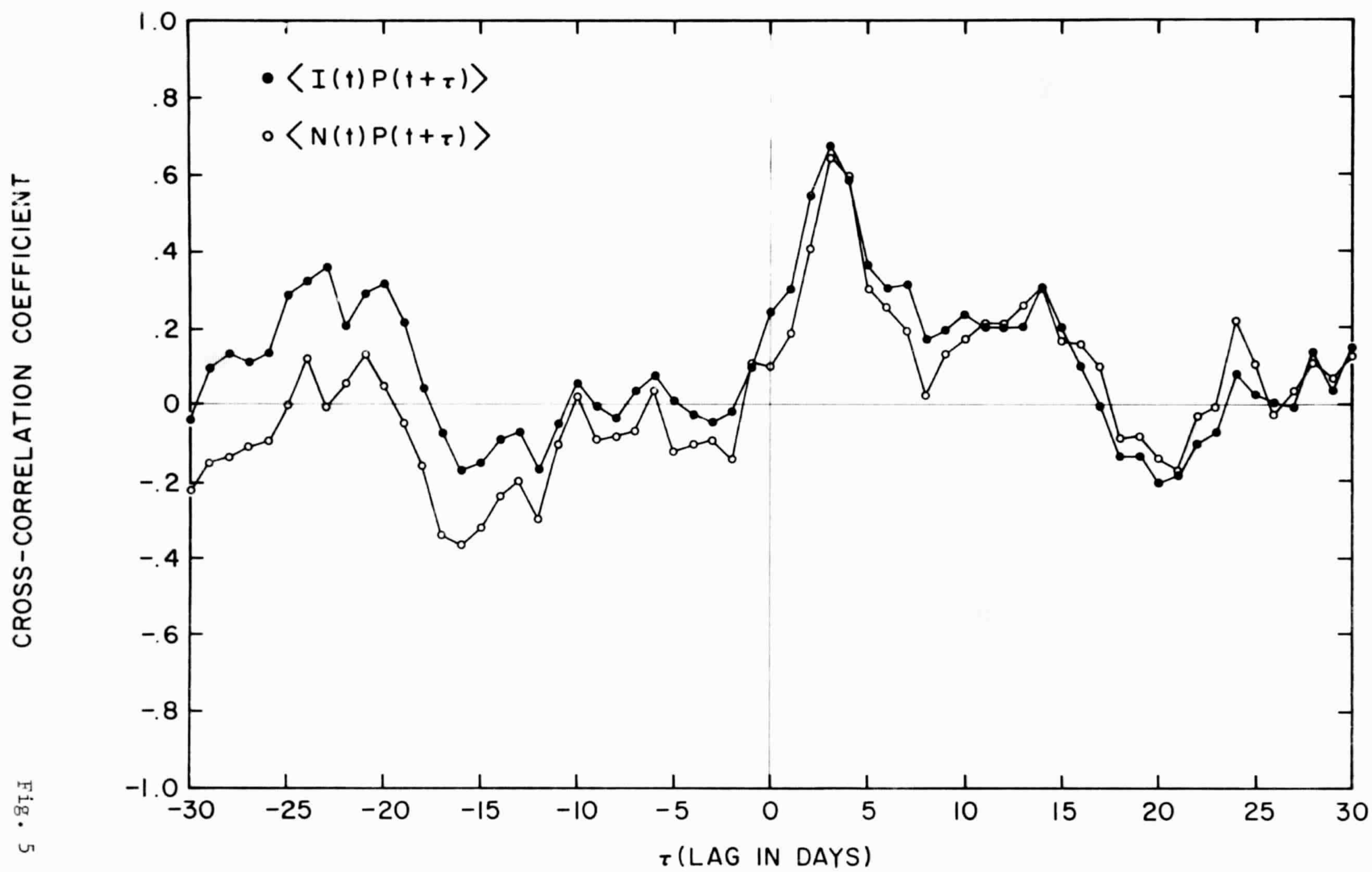

⟨N(t)N(t+τ)⟩
⟨I(t)I(t+τ)⟩
⟨N(t)I(t+τ)⟩
CROSS-CORRELATION COEFFICIENT
τ (LAG IN DAYS)
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1.0
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30

Fig. 4



CROSS-CORRELATION COEFFICIENT
1.0
.8
.6
.4
.2
0
-.2
-.4
-.6
-.8
-1.0
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
τ (LAG IN DAYS)
● ⟨I(t)P(t+τ)⟩
○ ⟨N(t)P(t+τ)⟩

Fig. 5